Original scientific paper – *Izvorni znanstveni rad*

Bunching with a Self-levelling Feller-Buncher on Steep Terrain for Efficient Yarder Extraction

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Abstract – Nacrtak

A research trial was conducted in Victoria, Australia, to evaluate a self-levelling feller-buncher on steep terrain and its potential to improve the overall productivity of steep terrain cable logging. The production study was conducted for a mechanized harvesting system using a Valmet 445 EXL self-levelling tracked feller-buncher and a Madill 124 swing yarder while operating in a clear fell plantation. This study quantified the equipment productivity of steep slope harvesting in a 33 year-old Pinus radiata *D. Don (radiata pine) plantation. Mechanized felling was an integral part of this operation, although there were areas of motor-manually felled trees due to terrain and stream restrictions. Thus the difference in productivity of the yarder for bunched and unbunched trees was quantified.*

For an average piece size of 0.8 m^3, a productivity of 138 m^3/PMH was predicted for the feller-buncher. Bunching substantially improved the productivity of the swing yarder. Mean volume per cycle for the swing yarder was 1.9 m^3 for bunched trees versus 1.3 m^3 for unbunched trees. For a yarding distance range between 150 and 240 metres, bunching increased the productivity by 25%. These results show the potential of self-levelling feller-bunchers in cable logging operations and suggest that research into mechanised felling be directed towards acquiring more information on the performance of steep terrain feller-bunchers in larger trees sizes, and under other slope and soil conditions in Australia.

Keywords: self-levelling feller-buncher, swing yarder, bunched trees, harvesting productivity

1. Introduction – *Uvod*

Worldwide there is a trend towards increased mechanization of forest harvesting operations. Advantages of mechanized felling include: increased production rate compared to manual felling; providing the opportunity to bunch stems for higher extraction productivity; improved value recovery through reduced stump height and tree breakage; and reducing operator exposure to physical harm (Murphy 2003, Visser 2008, Evanson and Amishev 2010).

Logging contractors have been recently using self-levelling feller-bunchers for steep slope harvesting in cable logging/yarder operations in parts of Australia and New Zealand. Purpose-built level-swing tracked feller-bunchers have been available for more than 30 years and have been used both in Australia and New Zealand clearfell harvesting operations for at least the last 15 years (Evanson 2010). A self-levelling feller-buncher increases the payload in comparison to a conventional feller-buncher as, in the latter case, the superstructure tends to swing downhill under the force of gravity with a resultant reduced lifting capacity. Also, tilting the cab too steeply makes it very uncomfortable for the operator (MacDonald 1999). Bunching harvesters not only improve efficiency compared with manual felling, they influence the following cable yarder productivity by concentrating the logs into bunches.

Bunching is not a new concept; its effect on yarder productivity was first investigated in the seventies in the USA (Kellogg 1976). It has been extensively used for improving extraction in plantations and natural forests (Spinelli and Hartsough 2000) and thinning and clearfelling (Bergström et al. 2010). Technology developed in recent years has made it possible to harvest on terrain well over 35 – 45% with the use of feller bunchers and harvesters (Carson et al.

1985, Kirk and Kellog 1990, Visser and Stampfer 1998). Stampfer and Steinmuller (2001) studied a tracked harvester Valmet 911 named »Snake« (whose four single wheels were replaced with trapezoidal tracked undercarriages) on slopes between 22% and 56%. In comparison to a thinning operation, an 11% increase in productivity was obtained in a clearfell operation for a slope of 36% and tree volume of 0.6 m^3. In a commercial thinning operation with a Syncrofalke yarder in Austria, Heinimann et al. (1998) reported increases in productivity of 25% for a yarder when trees were felled and logs bunched with a Skogsjan 687 harvester. In New Zealand, Amishev and Evanson (2010) investigated the extraction phase of the system that used an excavator log-loader to bunch stems and present them to the grapple yarder. The use of excavator bunching/presenting resulted in a significantly larger haul size to be extracted than grapple yarding using a spotter (3.2 versus 2.4 trees/cycle), which accounted for a 33% increase or an estimated 17 m^3/PMH extra production.

Based on these good experiences and the interest in mechanized felling and bunching, especially for cable extraction, a research trial was conducted to explore the potential of a mechanized felling/bunching system that could be utilised more extensively in Australia. The aim of this study was to evaluate a self-levelling feller-buncher on steep terrain and its potential to improve the overall productivity of steep terrain cable logging.

2. Materials and methods – *Materijal i metode*

2.1 Study site and layout – *Područje istraživanja*

The study site was located near Yarram, on the South Gippsland coast of Victoria, Australia (latitude/longitude: 38°30'45''S/146°33'54''E). The stand was a 33-year-old radiata pine plantation of approximately 1065 trees/ha with no notable understory. The dry, sedimentary-based soils enabled good traction in the steep terrain. The principle objective of this clearfelling operation was to produce a mixture of sawlog and pulp material. This site had never been thinned or pruned. A 0.58 ha plot containing 618 trees was laid out for observation of the feller-buncher; a pre-treatment description of the harvest plot is given in Table 1. The swing yarder was observed in an adjacent area (of approximately 0.6 ha and separated from the feller-buncher plot by about 50 metres) over a period of two days performing normal operations. A description of the felling of the trees and the layout of the area is presented in Fig. 1.

Operational harvest scheduling and equipment allocation made it not possible to conduct the feller-buncher and the swing yarder time study on exactly the same plot. However, both areas were consistently felled and yarded by the same operators and their work methods were identical on both sides. In addition, a visual inspection was also conducted to make sure that the bunches were similar in both areas. Although a detailed inventory was not carried out in the yarding area, plot data collected with the Atlas cruiser inventory system (ATLAS Technology 2010) was provided for the study area to confirm that tree size and the diameter distribution was similar in the feller-buncher and swing yarder area.

The feller-buncher machine with a self-levelling cab was responsible for felling and bunching all trees except those that the machine was unable to fell in a nearby creek due to environmental constraints. The creek area was demarcated with pegs and tapes to clearly identify the remaining trees that were motor-manually felled and consequently not bunched. It was not possible to layout two parallel corridors, one with pre-bunched trees and other with no pre-bunched trees, due to the high costs that repre-

Table 1 Pre-treatment description of the harvest plot
Tablica 1. *Osnovni podaci o mjestu sječe*

Plot Attribute *Svojstva istraživane plohe*	Value or range *Raspon podataka*
Mean DBH, cm – *Srednji prsni promjer*, cm	31.5
DBH range, cm – *Raspon prsnih promjera stabla*, cm	12 to 47
Mean tree size, m^3 – *Prosječni obujam stabla*, m^3	0.8
Tree size range, m^3 – *Raspon obujma stabala*, m^3	0.14 to 1.89
Mean basal area, m^2/ha – *Srednja temeljnica*, m^2/ha	82.6
Ground slope range, % – *Nagib terena*, %	32 to 47

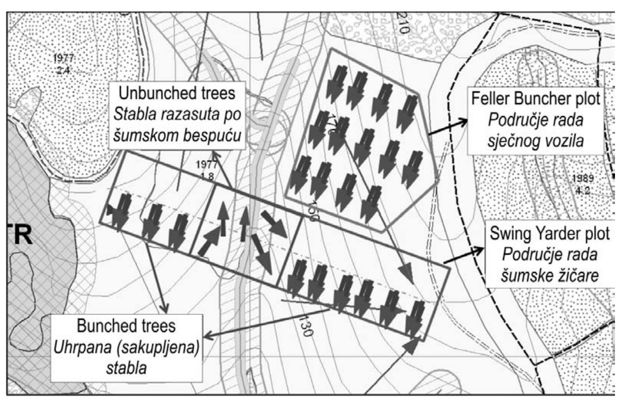

Fig. 1 Layout of the study area
Slika 1. *Prikaz područja istraživanja*

Fig. 2 Feller-Buncher »Valmet« 445EXL
Slika 2. *Gusjenično sječno vozilo Valmet 445 EXL*

Fig. 3 Swing Yarder »Madill« 124
Slika 3. *Šumska žičara s hvatalom Madill 124*

sented for the contractor to motor-manually fell trees that were located out of creek areas. Although this issue does not affect the productivity comparison between bunched and unbunched trees, it could eventually limit the scope of the results obtained in the study.

2.2 Harvesting system and work method – *Sustav pridobivanja drva i radne metode*

The harvesting system comprised a Valmet 445 EXL tracked, swing-to-tree type feller-buncher, a Madill 124 swing yarder and grapple, a Komatsu PC 300 with a Waratah 622 processing head, a Hitachi 280LC excavator loader, a tail hold excavator and a bulldozer. For the purpose of this study only the feller-buncher and the swing yarder were time studied. The feller-buncher was equipped with a Valmet 233 fixed felling head (chain saw) and a self-levelling cab up to 27 degrees (Fig. 2). The Madill 124 swing yarder (57.6 tons and 450 HP) was equipped with an 18.3 meters yarding boom, paired with a mobile tailspar (30 ton excavator) (Fig. 3).

Harvesting with the feller-buncher was carried out in parallel extraction tracks that were 15 metres apart. The observed operating method was for the machine to work a felling swath directly up the slope (moving at right-angles to the contour), laying bunches at right-angles to the line of movement. Most of the time, trees were cut when moving uphill, and then slewed to the right (the best visibility for the operator). Trees felled tended to be in the uphill semicircle (from about 270 to 70 degrees) of the machine's working radius. The operator was able to fell only one tree at a time because of the characteristics of the felling head and the size (DBH and height) of the trees being handled.

The swing yarder was used to haul the trees to a central landing where they were processed into logs, sorted and decked. The yarder was paired with a mobile tailspar, which was a key element in the functionality of this yarding system. To maintain productive cycles, mobility at the back end of a cable operation was equally important. For that purpose, a 30 ton excavator with raised swivelling fairleads was used. The mobile tailspar (excavator) was operated by a man when road changes were needed. This person (»spotter«) also gave radio instructions to the operator (due to lack of sight from the cab) during the yarding phase.

At the top of the corridor, there was a log chute formed in front/beneath the swing yarder where the trees could be stacked until the processor could grab them and begin processing each stem. Once processed, the log loader would sort the logs into their respective place in the log-deck, ready for loading onto trucks. The feller-buncher and hand-faller worked several days ahead of the extraction crew to avoid machine conflicts and ensure there was wood on the ground at all times for extraction.

2.3 Data Collection – *Prikupljanje podataka*

Before data collection began, tree diameters at breast height (DBH) (1.3 m) were measured and marked using a colour coding system. Eight different colour codes were used, in 5 cm classes from 12 cm (± 2.5 cm) to 42 cm (± 2.5 cm). Ground slope was measured at several points, averaging 36% with 47% maximum slope. Over the period of two days, the operation of the feller-buncher was filmed with a video camcorder. As each tree was felled, the colour was recorded in order to identify the felling times by diameter classes later when evaluating the film. Tree size (m^3) for individuals was determined from volume equations and coefficients provided by the Atlas cruiser inventory system.

The swing yarder was filmed yarding both bunched and unbunched trees with the number of pieces per cycle being recorded throughout the filming. Pre-harvest inventory data and some tree measurements were used to calculate the average tree size for the bunched and the unbunched tree areas. Maximum yarding distance was 310 metres, with an average yarding distance of approximately 155 metres (range 25 – 300 metres) for the bunched trees and 195 metres for the unbunched trees (range 150 – 240 metres).

The detailed time study was conducted in the office by reviewing field operations recorded by the camcorder. The software Timer ProTM (Applied Computer Services Inc. 2007) with a PDA (DellTM Axim x51) and a spreadsheet, were used for recording equipment cycle times. Cycle times of the machines were divided into work elements that were considered typical of the harvesting process of each machine. In addition, variables believed to have an impact on the productivity of each piece of equipment were recorded together with the work elements. For the feller-buncher, this included tree size while for the swing yarder this included number of pieces per cycle, yarding distance and a dummy variable describing if the load was bunched or unbunched.

For two travel cycles, a GPS travel recorder was attached to the inside cab window and also on the felling head itself to record the machine's travel. The GPS receiver placement on the relatively protected part of the felling head produced improved data in comparison to the receiver attached to the inside cab window, which experienced poor positional data.

2.4 Data analysis – *Obrada podataka*

Data collected with the detailed time study were used to determine the productivity of the feller-buncher and swing yarder. The statistical analysis consisted of simple (feller-buncher) and multiple linear (swing yarder) regression models for predicting cycle times per tree and productivity. In the swing yarder model the dummy variable »Unbunched« took a value of 1 for unbunched trees and 0 for bunched trees. Models were checked against regression assumptions and evaluated with the multiple *R*-squared, the standard error of the residuals, and

Table 2 Summary of feller-buncher's time study
Tablica 2. *Studij rada i vremena sječnoga vozila*

Work element – *Radne sastavnice*	No. of Observations *Broj mjerenja*	Mean time per cycle, sec. *Srednja vremena po radnom ciklusu, s*	% of cycle time *Postotni udio u turnusu rada, %*
Move to tree, or Re-position *Premještanje vozila ka stablu ili izmještanje vozila*	305	2.5	12.0
Swing-to-fell – *Postavljanje sječne glave za rušenje*	618	6.1	29.2
Cut – *Sječa*	618	3.5	16.7
Swing-to-bunch *Postavljanje sječne glave za sakupljanje stabala*	618	6.6	31.5
Second cut, or Cut stump *Drugi rez ili rez na panju*	33	0.3	1.4
Fell and bunch dead – *Sječa i skupljanje sušaca*	19	0.4	1.9
Adjust bunch – *Uhrpavanje*	25	0.4	1.9
Travel – *Kretanje*	5	1.1	5.2
Total – *Ukupno*	618	20.9	100.0

Move-to-tree, Re-position: Machine moving uphill in a straight line between successive tree felling and bunching activities, or machine movement laterally, adjusting the move-to-tree line
***Premještanje vozila ka stablu ili izmještanje vozila**: Vozilo se kreće ka stablu uz nagib ili po slojnicama između radnih sastavnica rušenja ili sakupljanja stabala*

Swing-to-fell: Machine slewing and extending the boom to position the felling head to fell a tree
***Postavljanje sječne glave**: Namještanje hidraulične dizalice sa sječnom glavom u najbolji mogući položaj za sječu*

Cut : Saw operation to fell the tree – ***Sječa:*** *sječa stabala*

Swing-to-bunch: Slewing the felled tree and lower to the ground or onto a bunch
***Postavljanje sječne glave za sakupljanje stabala**: Spuštanje ustavljenoga stabla na tlo ili slaganje u skupinu oborenih stabala*

Second cut, Cut stump: A second extension of the saw to sever a tree not felled after the first cut, or a cut to lower the height of a stump
***Drugi rez ili rez na panju**: Dugi rez sječnom glavom ili spuštanje sječne glave niže na panju stabla*

Fell and bunch dead trees: Slewing, cutting and bunching or disposing of a dead tree – ***Sječa i skupljanje sušaca**: Sječa, sakupljanje ili uklanjanje sušaca*

Adjust bunch: Move trees in a bunch to reduce spread of the butts – ***Slaganje složaja**: Slaganje stabala u složaju radi smanjenja veličine složaja*

Travel: Machine movement (downhill) from the end of a felling swath to the start of the next – ***Kretanje**: Kretanje vozila niz nagib ka novoj sječnoj liniji* the *F*-statistic. The statistically significant difference of the cycle time models for the swing yarder (null hypothesis that coefficient associated with the dummy variable is equal to cero) was determined through an Extra-sum-of-squares *F*-test. Also, *t*-tests were conducted to determine the effect of diameter on felling time as well as the effect of DBH on other work elements. All the tests presented in the paper were conducted at the $p = 0.05$ level of significance. Productivity is reported in delay-free productive machine hours (PMH) following standard methodologies used in harvesting (Nurminen et al. 2006, Acuna and Kellogg 2008).

3. Results – *Rezultati*

3.1 Time and motion study – *Studij vremena i pokreta*

A total of 618 trees (158 bunching cycles) were timed for the feller-buncher. The time per tree associated with each work element in a full cycle is presented in Table 2. Swing-to-bunch and swing-to-fell were the most time consuming work elements, accounting for 31.5% and 29.5% of the total cycle time, respectively. Average bunch size was 4.2 trees ranging from 2 to 6 trees. On average there were 1.7 moves/bunch, 2.4 trees cut between each move element, and 10.1 seconds/bunch for move-to-tree and reposition elements.

Statistically significant differences of tree diameter class on cut time are presented in Table 3. Several of the mean cut times for the breast height diameter classes were significantly different, indicating a relationship between tree diameter and cut time (Fig. 4). Also, for the individual 5 cm diameter classes there was no significant difference between swing loaded

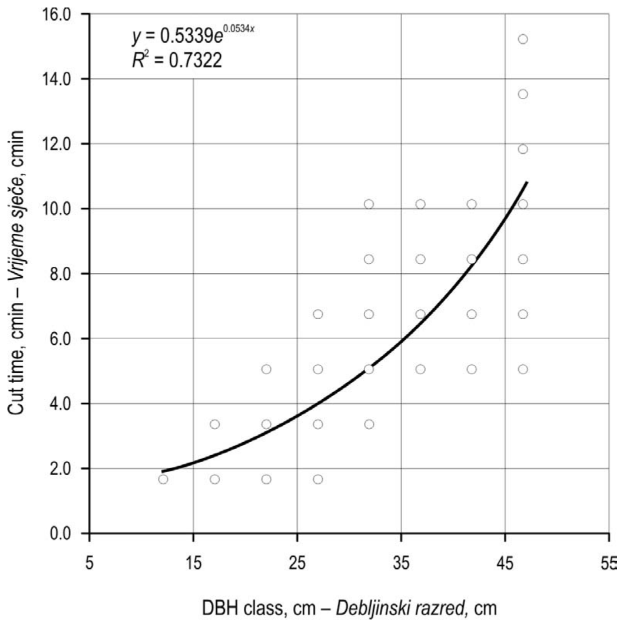

Fig. 4 Effect of DBH on cut time
Slika 4. *Utjecaj prsnoga promjera stabla na vrijeme sječe*

and bunch time (swing-to-bunch) and tree diameter. However, statistically significant differences between all classes were observed when combining data into larger classes (17 – 27 cm, 32 – 37 cm, 42 – 45 cm). Mean swing-to-bunch times were 5.6, 6.3, and 7.3 seconds for each class, respectively. As expected, larger trees required more time to swing-to-bunch.

Travel time per tree to return to start of the felling swath averaged 1.1 seconds/cycle (5 observations of 100, 177, 143, 174 and 176 seconds). Total machine movement time (including move-to-tree, re-position and travel elements) averaged 3.6 seconds/cycle or 17.2% of total cycle time. A downhill travel speed of 0.61 m/s (2.2 km/hr) was obtained from the data collected with the GPS. Average move-to-tree speed uphill, during felling and bunching was estimated at 0.47 m/s (1.7 km/hr).

A total of 184 haul cycles were collected during the swing yarder's time study. From this total, 142 cycles were completed from bunched trees and 42 cycles were completed from unbunched trees. The average number of pieces per cycle was 2.3 for the bunched trees and 1.5 for the unbunched trees, with an average volume per cycle of 1.9 m^3 (average tree size = 0.81 m^3) and 1.3 m^3 (average tree size = 0.87 m^3), respectively.

On a per cycle basis, drop/hook and outhaul times were 11.9% and 11.8% longer when yarding unbunched trees (Table 4). The bunched trees made a larger target for the operator to hit when dropping the grapple. Also, concentration of the trees in fewer

Table 3 Average cut times for diameter classes
Tablica 3. *Prosječno vrijeme sječe po debljinskim razredima*

Tree diameter class, cm *Debljinski razred*, cm	Mean cut time, sec. *Srednje vrijeme sječe*, s	Significant difference* *Signifikantna razlika**
12	1.6	a
17	1.7	a
22	2.0	a
27	2.3	b
32	3.1	c
37	3.8	d
42	4.4	e
47+	6.5	f

* Values with the same letter are not significantly different at $p > 0.005$
* *Vrijednosti iste oznake nemaju signifikantnu razliku za* p > *0,005*

Table 4 Summary of swing yarder's time study
Tablica 4. *Studij rada i vremena šumske žičare*

Work element – *Radne sastavnice*	Time (min) per cycle (bunched trees) *Vrijeme po turnusu rada (složena stabla)*, min	Time (min) per cycle (unbunched trees) *Vrijeme po turnusu rada (razasuta stabla)*, min
Swing-to-outhaul – *Odmicanje*	0.31 [14.9%]	0.30 [14.0%]
Outhaul – *Pomicanje praznoga hvatala*	0.34 [16.7%]	0.38 [17.6%]
Inhaul – *Pomicanje punoga hvatala*	0.81 [39.7%]	0.82 [38.0%]
Drop/hook – *Spuštanje hvatala i utovar*	0.59 [28.7%]	0.66 [30.4%]
Total – *Ukupno*	2.05 [100.0%]	2.18 [100.0%]

Swing-to-outhaul: Yarder swing after dropping a load at the landing chute and is ready to start a new outhaul
Odmicanje: *Odmicanje hvatala šumske žičare nakon istovara tereta na pomoćnom stovarištu*
Outhaul: Grapple movement downhill (empty) until it is lowered down to get a load
Pomicanje praznoga hvatala: *Pomicanje praznoga hvatala niz nagib do trenutka spuštanja hvatala zbog utovara*
Inhaul: Grapple movement uphill with a load of logs until the load is dropped at the landing chute
Pomicanje punoga hvatala: *Pomicanje hvatala s teretom do trenutka ispuštanja stabala na pomoćnom stovarištu*
Drop/hook: Grapple descending towards the ground until the logs have been secured and the grapple starts moving up towards the landing
Spuštanje hvatala i utovar: *Spuštanje hvatala prema tlu, utovar oborenih stabala do trenutka kretanja punoga hvatala*

locations improved overall visibility. Drop and hooking time ranged from 0.21 to 2.64 minutes/cycle for the unbunched trees and from 0.09 to 3.78 minutes/cycle for the bunched trees. The outhaul time difference is explained by the shorter yarding distance of the bunched trees in comparison with the unbunched trees (155 versus 195 metres). As expected, and considering all the cycles, outhaul time was statistically different at different distance ranges (25 – 100, 100 – 200, 200 – 300 metres). On average, outhaul time increased at a rate of 1.2 seconds for every 10 metres.

No substantial differences between bunched and unbunched trees were revealed in the cycle time for the elements swing-to-haul and inhaul. Swing-to--haul is independent of the yarding distance or turn size. In the case of inhaul, the effect of a shorter yarding distance for the bunched tree system was offset by the greater number of pieces and payload per cycle. On average, for the same yarding distance (between 150 and 240 metres), the inhaul time was reduced by 0.40 minutes when yarding unbunched trees, which resulted from the fewer pieces per cycle and the lower payload hauled to the landing. As depicted in Fig. 5, one or two pieces were hauled in more than 90% of the unbunched tree cycles. This contrasts with the bunched tree cycles where there was an even distribution of one, two, and three pieces (which accounted for about 85% of the cycles), with four and five pieces being hauled in the remaining 15% of the cycles. As in the case of outhaul time, inhaul time was statistically different at different distance ranges (25 – 100, 100 – 200, 200 – 300 metres). On average, inhaul time increased at a rate of 3 seconds for every 10 metres.

3.2 Cycle time and productivity models
Vrijeme ciklusa rada i modeli proizvodnosti

Linear regression models developed to determine the effect of tree size on the feller-buncher's cycle time per tree, and the effect of bunching, number of pieces per cycle and yarding distance on the yarder's cycle time per turn are presented in Table 5. Both models met the regression assumptions and all the variables were statistically significant. In the yarder model, the null hypothesis that the coefficient associated with the dummy variable is equal to zero was rejected through the Extra-sum-of squares *F*-test, indicating a significant difference between the models with and without the dummy variable.

Based on the results obtained with the models, piece size explains 32% of the feller-buncher's cycle time variance. The number of cycles per PMH drops by 19.1% (from 196.1 to 158.7) when tree size increases from 0.1 to 1.3 m^3 (Fig. 6). For an average tree size of 0.8 m^3, the model predicts 172.4 cycles (trees)/PMH.

In the case of the swing yarder, 62% of the cycle time per turn variance is explained by yarding distance, number of trees per cycle and bunching system. For a yarding distance ranging between 150 and 240 metres, and 2.3 and 1.5 pieces/cycle for the bunched and unbunched tree systems, the cycle time predicted with the model is 0.37 minutes shorter for the unbunched trees than for the bunched trees. On average, this represents 3.2 extra cycles/PMH for the unbunched tree system.

Productivity curves were obtained from the cycle time models developed for the feller-buncher and the swing yarder. Fig. 6 shows the feller-buncher's productivity curve for a range of tree sizes. For a tree

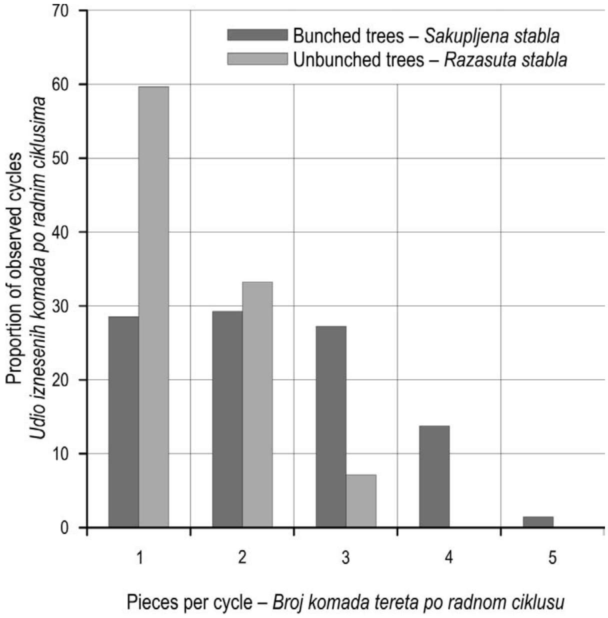

Fig. 5 Proportion of pieces per cycle for bunched and unbunched trees
Slika 5. *Udio komada tereta u radnom ciklusu za složena i razasuta stabla*

size range between 0.1 and 1.3 m^3, the productivity increases from 19.6 to 206.3 m^3/PMH. For an average tree size of 0.8 m^3, the model predicts a productivity of 138.0 m^3/PMH.

Fig. 7 shows the swing yarder's productivity curve for bunched and unbunched trees using 2.3 and 1.5 pieces/cycle, respectively. For the yarding distance range from where the bunched trees were collected (150 to 240 metres), productivity boosts by 25% (7.5 m^3/PMH) when bunched trees are yarded. The increased productivity of the bunched tree system is proportionally larger as yarding distance increases. Thus, for a yarding distance of 150 and 240 metres, productivity for the bunched trees is 22% and 27% higher than for the unbunched trees.

Table 6 compares the productivity between bunched and unbunched trees for a yarding distance of 180 metres. On average, the cycle time for the bunched trees is 17% longer than for the unbunched trees (2.8 minutes versus 2.4 minutes) with the corresponding fewer number of cycles per PMH (21.5 versus 24.7). However, the longer average time per cycle for the bunched trees is offset by a 33% increase in the number of pieces per PMH, which results in a 24% increase in the volume yarded per PMH (40.1 m^3 for bunched trees versus 32.3 m^3 for unbunched trees).

The surface chart in Fig. 8 shows the combined effect of yarding distance and number of pieces per cycle on the swing yarder's productivity when bunch-

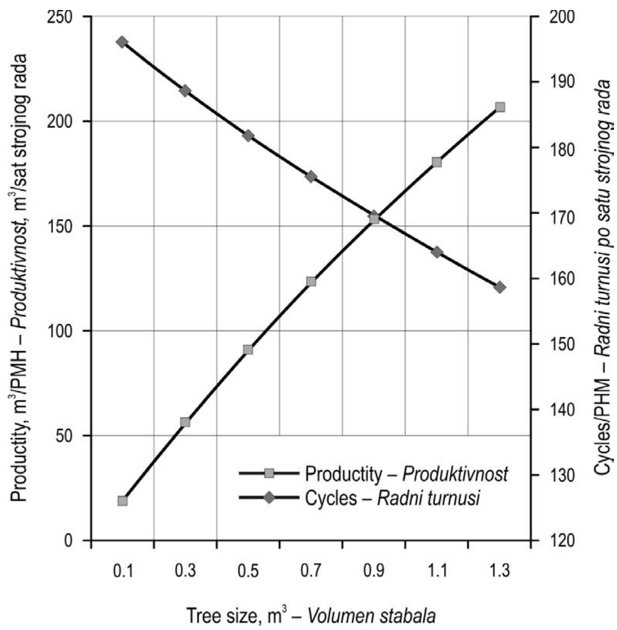

Fig. 6 Feller-buncher's productivity curve and cycles per PMH for a range of tree sizes
Slika 6. *Krivulja proizvodnosti sječnoga vozila*

Table 5 Cycle time models for feller-buncher and swing yarder
Tablica 5. *Modeli radnih ciklusa za sječno vozilo i šumsku žičaru*

Feller-buncher – *Sječno vozilo*
Cycle time, min/cycle = 0.30 + 0.06 x Tree size, m^3 – *Vrijeme radnoga ciklusa,* min/turnusu *= 0.30 + 0.06 x obujam stabla,* m^3
Residual standard error: 0.042 on 616 *df* – *Preostala standardna pogreška: 0,042 za 616 stupnjeva slobode*
Multiple r^2 = 0.32, 618 observations – *Multipla regresija* r^2 *= 0,3 za 618 mjerenja*
F-statistic: 170.1 on 1 and 616 *df*, *p*-value = 0 – F-*statistika: 170,1 za 1 i 616 stupnjeva slobode;* p-*vrijednost = 0*
Swing yarder – *Šumska žičara*
Cycle time, min/cycle = 1.11 + 0.01 x Distance, m – 0.05 x N, pieces/cycle – 0.41 x Unbunched (0/1) *Vrijeme radnoga ciklusa,* min/turnusu *= 1,11 + 0,01 x Udaljenost iznošenja* (m) – 0,05 x N, komada/turnusu – 0,41 x *razasuta stabla* (0/1)
Residual standard error: 0.504 on 180 *df* – *Preostala standardna pogreška: 0,504 za 180 stupnjeva slobode*
Multiple r^2 = 0.62, 184 observations – *Multipla regresija* r^2 *= 0,62 za 184 mjerenja*
F-statistic: 97.48 on 3 and 180 *df*, *p*-value = 0 – F-*statistika: 97,48 za 3 i 180 stupnjeva slobode;* p-*vrijednost = 0*

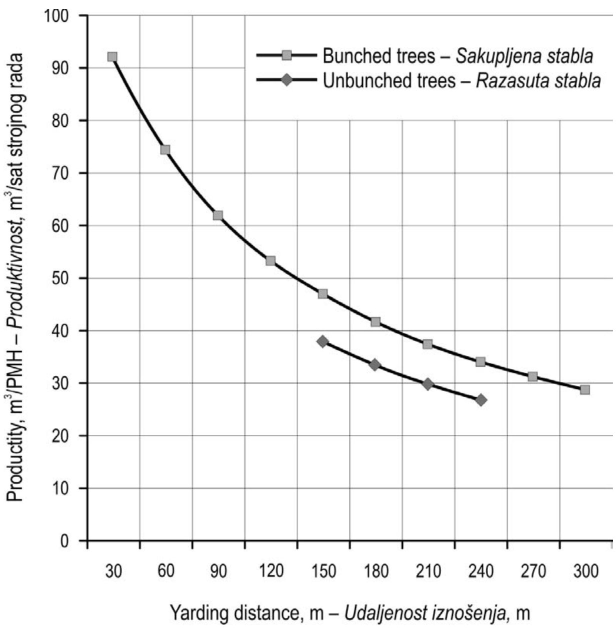

Fig. 7 Swing yarder's productivity curve for bunched and unbunched trees
Slika 7. *Krivulja proizvodnosti šumske žičare za (ne)sakupljena stabla*

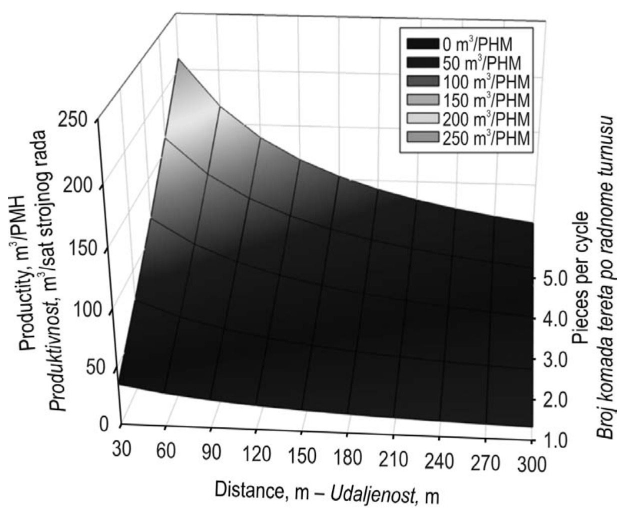

Fig. 8 Effect of yarding distance and number of pieces per cycle on the swing yarder's productivity (bunched trees)

Slika 8. *Utjecaj udaljenosti iznošenja drva i broja komada po radnom turnusu na proizvodnost šumske žičare (za sakupljena stabla)*

ed trees are yarded. For an average yarding distance of 150 metres, there is a five-fold increase in productivity (from 19 m^3/PMH to 103 m^3/PMH), when the number of pieces per cycle increases from 1 to 5. The effect of pieces per cycle is slightly bigger with shorter yarding distances. Thus, when tree size increases from one to five, productivity boosts about 5.86 times for a yarding distance of 30 metres (from 36 m^3/PMH to 210 m^3/PMH) and about 5.25 times

Table 6 Productivity measurements for bunched and unbunched trees (yarding distance = 180 metres)
Tablica 6. *Mjerenja proizvodnosti za sakupljena i razasuta stabla pri udaljenosti privlačenja od 180 m*

Attribute – *Značajke*	Bunched trees *Skupljena stabla*	Unbunched trees *Razasuta stabla*
Average time per cycle, min *Prosječno vrijeme trunusa, min*	2.8	2.4
Cycles/PMH *Turnusi/satu strojnoga rada*	21.5	24.7
Average no. pieces/PMH *Prosječan broj komada po satu strojnoga rada*	49.5	37.1
Average volume/PMH*, m^3 – **Prosječni obujam komada, m^3 po satu strojnoga rada**	40.1	32.3

* Based on an average piece size of 0.81 m^3 for the bunched trees and 0.87 m^3 for the unbunched trees
* *Prosječni obujam komada od 0,81 m^3 za sakupljena stabla i 0,87 m^3 za razasuta stabla*

for yarding distance of 300 metres (from 12 m^3/PMH to 63 m^3/PMH). The figure also shows that in proportion, yarding distance has a slightly greater effect on productivity when more pieces per cycle are hauled. Thus, when yarding distance increases from 30 to 300 metres, there is a 3-fold increase in productivity for cycles where one piece is yarded (from 12 m^3/PMH to 36 m^3/PMH), and a 3.3-fold increase in productivity for cycles where five pieces are yarded (from 63 m^3/PMH to 209 m^3/PMH).

4. Discussion – *Rasprava*

The aim of this study was to evaluate a self-levelling feller-buncher on steep terrain and its potential to improve the overall productivity of steep terrain cable logging.

Previous studies have identified tree size as a major issue with tracked feller-buncher performance (Acuna and Kellogg 2008). Both tree size (mass) and DBH affect cutting time, and the ability to swing and bunch or drop the tree. Previous studies in medium to large tree size clearfelling operations in Australia and New Zealand have compared productivity rates of self-levelling feller-bunchers. In a recent study, in atypical New Zealand conditions of high stocking (736 stems/ha) and small tree sizes (1.0 m^3), a Valmet 445 EXL equipped with a Satco 630 felling head achieved a productivity of 100 trees/PMH. Slopes travelled averaged 19.4% and move time in this stocking comprised 16% of total cycle time (Evanson 2008). This current study confirmed that both felling (cut-time) and bunching (swing-to-bunch time) were significantly affected by DBH and tree size. In our study, maximum tree size of around 50 cm DBH did not appear to present any problems for the machine and larger trees were felled and bunched using the same methods as average sized trees (31.5 cm DBH). We are aware that the sole inclusion of tree size, although statistically significant, affected the predictive capability of the feller-buncher's cycle time and productivity models, with the corresponding low R-squared values. Some researchers (e.g. Pan et al. 2008) have developed models that include additional independent variables such as »move to tree distance« and »move to bunch distance«, which have resulted in more accurate cycle time models and high R-squared values. However, these variables are time consuming and difficult to collect in the field, and the use of these models are limited for operational staff when felling takes place in different harvest and forest conditions.

Feller-buncher performance is also affected by stocking. In our study, the high stocking of 1000 stems per hectare enabled a high ratio of trees to be felled per move-to-tree element (average 2.4). Move-to-tree time was also affected by the required bunch size. The average bunch size was four trees (varying from two to six trees depending on tree size) to try to match the grapple capacity so that by each haul the grapple could extract a complete bunch for maximum efficiency.

For the swing yarder, total cycle time per turn increased by 12% when yarding bunched trees, mainly due to the longer inhaul time involved when yarding more volume per cycle. However, on a per cycle basis, drop/hook for bunched trees was 11% shorter than for unbunched trees. The easily visible bunches provided a larger and easier target for the yarder operator to engage the grapple which reduced drop/hook times for the bunched trees. It is clear though that some time was used in making bunch sizes that were not suited to the grapple capacity. Although the feller-buncher was able to produce bunches with an average of 4.3 trees, only 2.3 trees/cycle were hauled to the landing. This is mainly explained by the holding capacity of the grapple and the necessity for the operator to maintain yarder productivity without spending excessive time hooking logs.

Despite the fact that bunching could eventually affect the feller-buncher productivity and that bunch sizes were not suited to the grapple capacity, the most noticeable difference observed between bunched and unbunched trees was the greater number of pieces per cycle in bunched stems (2.3 versus 1.5), which on average resulted in a 25% increase in productivity for the swing yarder. The results are very similar to some reported in previous studies. In New Zealand, different breakout methods resulted in different number of trees hauled per cycle (Evanson and Amishev 2010). For an average tree size of 0.85 m^3, 2.4 trees/cycle were hauled when the trees were grappled using a spotter and 1.5 trees/cycle (mainly unbunched) were hauled when trees were grappled by the yarder operator only. The use of excavator bunching/presenting resulted in a 33% increase (17 m^3/PMH) extra production.

Both yarding distance and number of pieces per cycle showed to have an important impact on the yarding productivity, especially at shorter distances and when more pieces per cycle were yarded. Yarding productivity was slightly more sensitive to the number of pieces per cycle than to yarding distance. Although cycle times increased by 15% when bunched trees were yarded (more pieces per cycle), this effect was offset by the additional volume per cycle, which in turn resulted in a higher productivity per PMH. These results are consistent with other studies found in the literature. In Canada, Peterson (1987) reported a 57% increase in the number of pieces yarded per PMH when bunched trees were yarded (average piece size = 0.75 m^3). For a yarding distance of 150 metres, cycle time for bunched trees was 5% longer than for unbunched trees, mainly explained by a 20% increase in inhaul time.

5. Conclusions – *Zaključci*

Results of this study indicate that in good conditions (relatively small clearfell tree size – average 0.8 m^3 – and dry, sedimentary-based soils that enabled good traction on slopes of 36 to 47%) a high production rate can be achieved by a tracked self-levelling feller-buncher.

Mechanical felling and bunching operations are particularly advantageous if working in smaller tree sizes because extraction efficiency can be improved through bunching for optimal yarding sizes. For an average piece size of 0.8 m^3, a productivity of 138 m^3/PMH was predicted for the feller-buncher. Bunching improved substantially the productivity of the swing yarder. The mean volume per cycle for the swing yarder was 1.9 m^3 for the bunched trees versus 1.3 m^3 for the unbunched trees. For a yarding distance range between 150 and 240 metres, bunching increased the productivity of the swing yarder by 25%.

Despite the limitations of our study (one stand with specific terrain and forest conditions, study layout, productivity model for the feller-buncher based solely on tree size, no time study of felling without bunching), these results show the potential of self-levelling feller-bunchers in cable logging operations and suggest that research into mechanized felling be directed towards acquiring more information on the performance of steep terrain feller-bunchers in larger pieces size, and under other slope and soil conditions in Australia.

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Sažetak

Utjecaj sakupljanja stabala feler-bančerom na strmom terenu na učinkovito iznošenje drva žičarom

*Istraživanje rada sječnoga vozila na strmim terenima, njegove mogućnosti i poboljšanja u proizvodnosti u pridobivanju drva užetnim sustavima na strmim terenima provedeno je u saveznoj državi Viktorija u Australiji. Obavljena je strojna čista sječa i iznošenje drva u 33-godišnjoj plantaži bora (*Pinus radiata *D. Don) pomoću* *sječnoga vozila Valmet 445 EXL i šumske žičare Madill 124. Strojna je sječa okosnica ovoga istraživanja, iako treba napomenuti da je zbog terenskih prilika na pojedinim dijelovima sastojine obavljena i ručno-strojna sječa motornom pilom lančanicom. Razlika u proizvodnosti rada šumske žičare promatrana je usporedbom prethodno sakupljenih i oborenih stabala sječnim vozilom i onih posječenih motornom pilom i razasutih po šumskom bespuću.*

Rezultati ovoga istraživanja pokazuju da je u povoljnim sastojinskim uvjetima (relativno mala veličina stabala – prosječnoga obujma 0,8 m^3, te na ocjeditim sedimentnim tlima) omogućena dobra kretnost vozila na nagibima od 36 do 47 % s visokom proizvodnosti. Na temelju regresijskoga modela izračunata je proizvodnost sječnoga vozila od 138 m^3/h za prosječni obujam stabla od 0,8 m^3.

Na proizvodnost šumske žičare uvelike je utjecalo da li su stabla bila prethodno sakupljena ili su bila razasuta po šumskom bespuću nakon sječe. Sakupljanje oborenih stabala omogućilo je skraćivanje turnusa rada šumske žičare jer je spuštanje hvatala i prihvat tereta bilo kraće za 11 %. Lako vidljive grupe (oborenih pa sakupljenih) stabala omogućile su operateru šumske žičare lakše i točnije usmjeravanje hvatala, pa je i vrijeme prihvata tereta bilo kraće. Iako je sječnim vozilom Valmet 445 EXL moguće skupiti u prosjeku 4,3 stabla po grupi (složaju), samo su 2,3 stabla iznesena na pomoćno stovarište u jednom turnusu. To je uglavnom zbog veličine hvatala same šumske žičare i nastojanja radnika za smanjenjem gubitka vremena pri prihvatu tereta.

Unatoč činjenici da bi sakupljanje oborenih stabala na kraju moglo utjecati na proizvodnost samoga sječnoga vozila te iako veličine sakupljenih stabala nisu bile prikladne za hvatalo žičare, zamjetljiva razlika između sakupljenih i razasutih stabala jest veći broj iznesenih komada po radnom turnusu (2,3 komada/turnusu kod skupljenih stabala, nasuprot 1,5 komada/turnusu kod stabala razasutih po šumskom bespuću), s prosječnim obujmom iznesenoga drva od 1,9 m^3/turnusu za skupljena stabla, u odnosu na 1,3 m^3/turnusu za razasuta stabla. U prosjeku je za udaljenosti iznošenja drva od 150 do 240 metara sakupljanje oborenih stabala povećalo proizvodnost šumske žičare s hvatalom za 25 %.

Unatoč ograničenjima ovoga istraživanja (istraživanje je provedeno u jednoj sastojini, model proizvodnosti sječnoga vozila Valmet 445 EXL temelji se isključivo na prosječnoj veličini oborenih stabala, nije izrađena studija rada i vremena od dviju sastavnica, tj. posebno sječa stabala pa onda sakupljanje oborenih stabala, ovi rezultati pokazuju mogućnosti korištenja (sječa te sakupljanje) gusjeničnih sječnih vozila uz iznošenje drva šumskim žičarama na strmim terenima u Australiji. Potrebna su daljnja istraživanja na različitima terenima, nagibima te tipovima tla, ali i pri obaranju stabala većih dimenzija.

Ključne riječi: gusjenično sječno vozilo, šumska žičara, sakupljanje stabala, proizvodnost

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